Evaluating Design Proposals for Complex Systems with Work Domain Analysis

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In this paper we propose a new framework for evaluating designs based on work domain analysis, the first phase of cognitive work analysis. We develop a rationale for a new approach to evaluation by describing the unique characteristics of complex systems and by showing that systems engineering techniques only partially accommodate these characteristics. We then present work domain analysis as a complementary framework for evaluation. We explain this technique by example by showing how the Australian Defence Force used work domain analysis to evaluate design proposals for a new system called Airborne Early Warning and Control. This case study also demonstrates that work domain analysis is a useful and feasible approach that complements standard techniques for evaluation and that promotes a central role for human factors professionals early in the system design and development process. Actual or potential applications of this research include the evaluation of designs for complex systems.

INTRODUCTION

Cognitive work analysis (Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999) has most commonly been used for the design and evaluation of *interfaces* for complex systems (e.g., Burns, 2000; Dinadis & Vicente, 1999; Pejtersen & Rasmussen, 1997; Rasmussen, 1998; Vicente, 1995). More recently, however, we have shown that cognitive work analysis can be extended beyond interface design to the design of *entire systems* and to all phases of a system's life cycle, from requirements definition to system retirement (Naikar, Lintern, & Sanderson, in press; Sanderson, Naikar, Lintern, & Goss, 1999; Sanderson, 2000). Our focus in this paper is to show how work domain analysis, the first phase of cognitive work analysis, can be used to evaluate design proposals for complex systems, such as military aircraft.

Traditionally, the role of human factors professionals in test and evaluation of designs has involved assessing the human performance implications of alternative design solutions (Meister, 1986). Unfortunately, experience has shown that the advice provided by human factors experts is often ignored or is left until it is too late to incorporate into design (e.g., Charlton & O'Brien, 1996; Czaja, 1997; Walsh, Lim, & Long, 1989; Whitefield, Wilson, & Dowell, 1991). To encourage human factors advice to be taken seriously, new steps are necessary for promoting the role of human factors practitioners in system design and development. We believe that work domain analysis offers a means for fulfilling this goal.

In this paper we present work domain analysis as a framework for evaluating designs in the context of military acquisition. In particular, we focus on the early stages of acquisition, when a buyer evaluates several proposals that have been submitted by various manufacturers for the design of an intended system. This process is called *tender evaluation* in the United Kingdom and Australia and *source selection* in the United States of America. The aim of this

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process is to determine which of the proposals will best satisfy user needs. This is an important stage of acquisition because following this decision the buyer becomes locked into a particular design concept, and further evaluation is focused on modifying or refining the chosen design.

In the following sections we develop a rationale for a new approach to evaluating designs by describing the unique characteristics of complex systems and by discussing the limitations of systems engineering techniques in accommodating these characteristics. We recognize that our arguments are relevant to a broad range of systems, not only military systems, and to many different kinds of evaluation, not just the evaluation of design proposals. Nevertheless, we concentrate mainly on the use of work domain analysis for evaluating design proposals for military systems because this is the only context in which we have used this framework so far.

Evaluating Designs for Complex Systems

Complex systems have special characteristics that place unique requirements on the evaluation of designs. First, complex systems consist of an interdependent set of human and machine components that must interact to achieve the work requirements of the system. This implies that a framework for evaluating designs must be concerned not only with the performance of individual components in the system but also with the interactions between the components. In addition, the criteria for evaluating the performance of the components must be aimed at whether they fulfill the work requirements of the system.

Second, the work requirements of complex systems can no longer be described by a stable set of task sequences or procedures (Meister, 1996; Rasmussen et al., 1994; Vicente, 1999). In modern systems with high levels of automation and computerization, the main role of human workers is to deal with novel or unpredictable contingencies, which pose a considerable threat to system performance and safety (Perrow, 1984; Pool, 1997; Reason, 1990; Vicente, 1999). In these situations, workers typically cannot rely on preplanned work procedures. Rather, flexible and innovative problem-solving behavior is critical for preventing the system from failing. A framework for evaluation must therefore accommodate judgments of whether a design will support a variety of work patterns in a dynamic work space.

Standard Techniques for Evaluating Designs

In this section we describe standard techniques for evaluating designs and show that these techniques only partially fulfill the requirements for evaluating designs for complex systems. These techniques, which are known as *technical* and *operational evaluation techniques,* are derived from systems engineering and are commonly used for military acquisition throughout the world (Charlton & O'Brien, 1996; Department of Defence, 1995, 1999; Gabb & Henderson, 1995, 1996; Malone, 1996; O'Brien, 1996). Although there may be slight differences in how the techniques are implemented across projects, the general approach is the same.

The technical evaluation involves examining the physical devices of a proposed design against a set of prespecified technical performance criteria. For example, relevant criteria for an aircraft's mission computer may include storage capacity, speed of processing, and reliability. By using this technique, evaluators develop a detailed understanding of the technical solution of a proposed design. However, each of the physical devices, and the human and machine performance implications of each device, are largely evaluated in isolation of one another.

The operational evaluation involves examining how the technical solution of a proposed design will perform in specific mission scenarios. This technique promotes an understanding of how a design will deal with the work requirements of a range of probable situations. However, because of logistical difficulties, the evaluation is usually limited to a small number of scenarios relative to the total work space of possibilities. Moreover, the mission scenarios are typically specified as sequences of tasks and events that can be anticipated by domain experts. Thus this technique has little to offer in determining how designs will perform in a broad range of situations, including changing or unanticipated conditions. Similar criticisms were made by Vicente (1999) of scenario-based design.

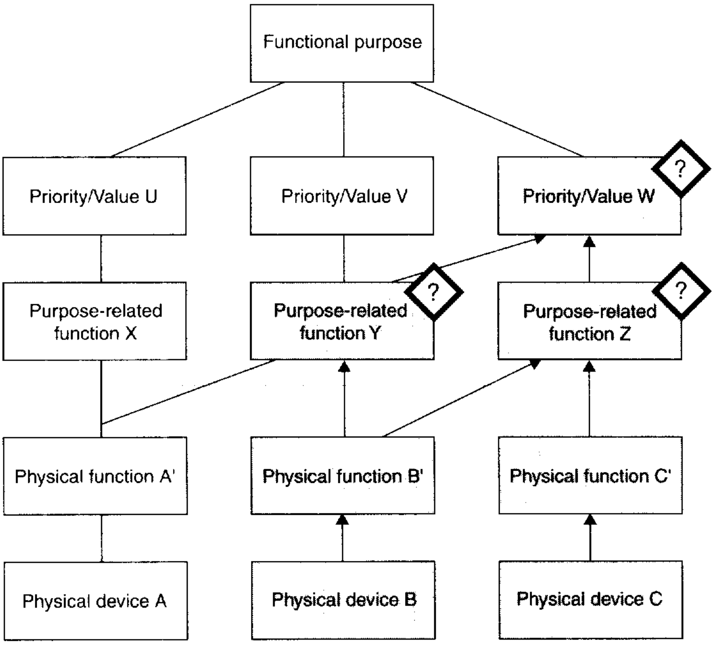

Figure 1. General format of an abstraction hierarchy illustrating how the design solutions relating to particular physical devices can be evaluated against the high-level functional properties of a work domain.

A Work Domain Analysis-Based Approach for Evaluating Designs

In this paper we propose a new framework for evaluation based on work domain analysis, the first of the five techniques of cognitive work analysis (Rasmussen et al., 1994; Vicente, 1999). Work domain analysis explicitly recognizes that complex systems are subject to a great many events that cannot be specified or enumerated in detail. Hence, rather than concentrating on specific scenarios or trajectories through a work space, work domain analysis focuses on the fundamental functional boundaries on system performance and safety. These functional boundaries are relevant to a broad range of situations, including scenarios that cannot be specified up front, and are thus described as event independent.

The functional boundaries of a work domain can be represented in an abstraction hierarchy (Figure 1). An abstraction hierarchy typically describes (a) the functional purposes or high-level objectives of a work domain; (b) the priorities and values that must be preserved in carrying out the work of the system; (c) the purpose-related functions or general functions that must be executed and coordinated to achieve work domain objectives; (d) the physical functions, such as those afforded by the physical devices of the work domain; and (e) the physical form, such as the physical devices themselves. The functions at each layer can also be decomposed into their constituent parts (see Naikar & Sanderson, 1999; Rasmussen et al., 1994; Vicente, 1999).

The links between the layers of an abstraction hierarchy express means-ends or how-why relations (Figure 1). Links from a target function to lower levels of abstraction indicate *how* a function is operationalized or engineered (means). Conversely, links from a target function to higher levels of abstraction indicate *why* that function exists (ends).

By using an abstraction hierarchy for evaluation, the physical-device solutions of a proposed design (physical form and physical function) can be evaluated in terms of how well they fulfill the higher-level functions and objectives of a work domain (purpose-related functions, priorities and values, functional purposes). For example, Figure 1 shows that Physical Device B and Physical Function B can be evaluated in terms of how well they support Purpose-Related Functions Y and Z. The effect on the purpose-related functions can then be evaluated against Priority/Values V and W and the functional purpose of the work domain.

The abstraction hierarchy can also be used to evaluate interactions among physical-device solutions. To illustrate, although the designs of Physical Devices B and C could each fulfill their technical performance criteria, the interactions between the solutions might compromise Purpose-Related Function Z and Priority/Value W. However, Physical Devices B and C might both have positive effects on Purpose-Related Function Z, which then shows up as an enhanced effect on Priority/Value W. Alternatively, Physical Device B may have a positive effect on Purpose-Related Function Z that cancels the negative effect that Physical Device C has on this function, so that overall there is no effect on Priority/Value W.

In summary, then, work domain analysis focuses evaluation on whether an interdependent set of physical-device solutions will interact effectively to fulfill the work requirements of a proposed system. These work requirements, which are defined by the purpose-related functions, priorities and values, and functional purposes of a work domain, are event independent. Thus, work domain analysis promotes an understanding of how designs will perform in a wide variety of situations, including changing or unpredictable contingencies.

EVALUATING DESIGNS FOR AIRBORNE EARLY WARNING AND CONTROL

Having outlined the theoretical motivations for a work domain analysis-based approach to evaluation, we will now explain this technique by example by showing how the Australian Defence Force used work domain analysis to evaluate design proposals for a new system, Airborne Early Warning and Control (AEW&C). This case study also highlights the benefits and challenges of using work domain analysis to evaluate designs, and compares it with standard evaluation techniques that were also used on this project. First, however, we provide a brief background of the AEW&C project to illustrate the Australian Defence Force's motivations for adopting work domain analysis.

AEW&C is a complex airborne system that is currently being manufactured by Boeing for the Australian Defence Force. When it is delivered to Australia, each AEW&C aircraft will be equipped with a suite of physical devices, including onboard sensors, satellite intelligence links, voice and data communications systems, and electronic warfare equipment. The crew of AEW&C will consist of a pilot, a copilot, and a team of people at the back of the aircraft who will be responsible for developing a situation picture and controlling defense assets in an allocated area of operations. This role is similar to that of the Airborne Warning and Control System of the U.S. Air Force.

Initially, the AEW&C Project Office was going to use only standard techniques to evaluate AEW&C designs that had been submitted by Boeing, Raytheon E-Systems, and Lockheed Martin. For the technical evaluation, evaluators would judge whether the design solutions for each of the physical devices of AEW&C complied with, exceeded, or were deficient with respect to prespecified performance requirements. For the operational evaluation, evaluators would develop computational models of the technical solutions of the three designs and then use Monte Carlo simulation to test the performance of the alternative designs in six mission scenarios.

During a preliminary evaluation using these techniques, the AEW&C Project Office realized that the technical evaluation would result in a series of disparate reports about each of the many physical devices of AEW&C. For example, a radar report might inform them that Design A was better than Designs B and C, a communications report might inform them that Design B was better than Designs A and C, and a mission system report might inform them that Design C was better than Designs A and B. The AEW&C Project Office quickly became very concerned about how they would integrate the recommendations of all of the technical reports to reach a final decision about the best AEW&C design.

When this problem was presented to the AEW&C evaluation team, of which we were members, it struck us that all of the physical devices of AEW&C were being designed into a single system to support a common set of functions, priorities and values, and purposes. Thus, work domain analysis could be used to carry out an integrated evaluation of all of the physical devices of AEW&C. Convincing the AEW&C Project Office to adopt this approach involved constructing a draft abstraction hierarchy and playing out how the evaluation would proceed using this approach. After the decision to use work domain analysis was made, we had only 1 year remaining to conduct a work domain analysis for AEW&C and to develop a process for using this approach for the final evaluation of AEW&C designs. It is difficult to determine the exact cost of the work domain analysis approach, but the cost of adding this approach to the AEW&C project was insignificant relative to the cost of the standard techniques.

AEW&C Work Domain Analysis

Our first step on the AEW&C project was to develop an abstraction hierarchy for AEW&C. We used various internal documents prepared by the Australian Defence Force, such as the AEW&C concept of operations and the AEW&C system specification, to develop a preliminary abstraction hierarchy. This initial representation was reviewed by several subject-matter experts, including military personnel and engineers, operations analysts, and scientists from the Defence Science and Technology Organisation. This work occurred over a period of 6 months, with the analysts working approximately half time during this period.

In reviewing the documents and interviewing subject-matter experts, we used the labels and descriptions of each layer of the abstraction hierarchy (Rasmussen et al., 1994; Vicente, 1999) to guide our search for particular kinds of information. So, for the functional purposes of AEW&C, we searched for information about why AEW&C was being purchased by the Australian Defence Force and how AEW&C would contribute to Australia's defense capability. For the priorities and values layer, we looked for information about the advantages that AEW&C would offer over potential adversaries in the area. For the purpose-related functions layer, we looked for information about the everyday functions that AEW&C would perform on a mission. Information about the physical form and physical functions of AEW&C were readily available in acquisition documents that listed the physical devices of AEW&C and the functionality of each device. To ensure that the abstraction hierarchy was internally consistent and complete, we asked ourselves and the subject-matter experts how-why questions about all of the functions we had represented.

The resulting AEW&C abstraction hierarchy has 2 functional purposes, 10 priorities and values, 12 purpose-related functions, 77 physical functions, and 61 physical devices. About 350 means-ends relations were used to check the internal consistency of the AEW&C abstraction hierarchy. Because of the size of this analysis, we cannot reproduce the entire AEW&C abstraction hierarchy here.

In Figure 2, however, we provide a sample of functions from each layer of the AEW&C abstraction hierarchy. The functional purposes layer illustrates that AEW&C will contribute not only to the defense of Australia but also to civil defense operations (e.g., search and rescue) and regional activities (e.g., disaster relief). To achieve these objectives, AEW&C must satisfy the priorities and values of a long-term understanding of patterns of regional activity, a real-time understanding of the current tactical situation, the coordination and safety of assets under its control, and self-preservation. The purpose-related functions that it must execute to fulfill the purposes of the work domain include development of the tactical picture, evaluation of the tactical situation, communication, and implementation of protective measures. Finally, AEW&C will be equipped with physical devices such as a radar for gathering information from the environment and a mission data-processing computer for storing and processing information.

The means-ends links in Figure 2 illustrate that evaluators can use the AEW&C work domain analysis to judge the impact of physical-device solutions on the higher-level functions of the work domain. Thus if the ability to exchange information and communicate is compromised through deficiencies in the equipment design, then the ability to establish, update, and

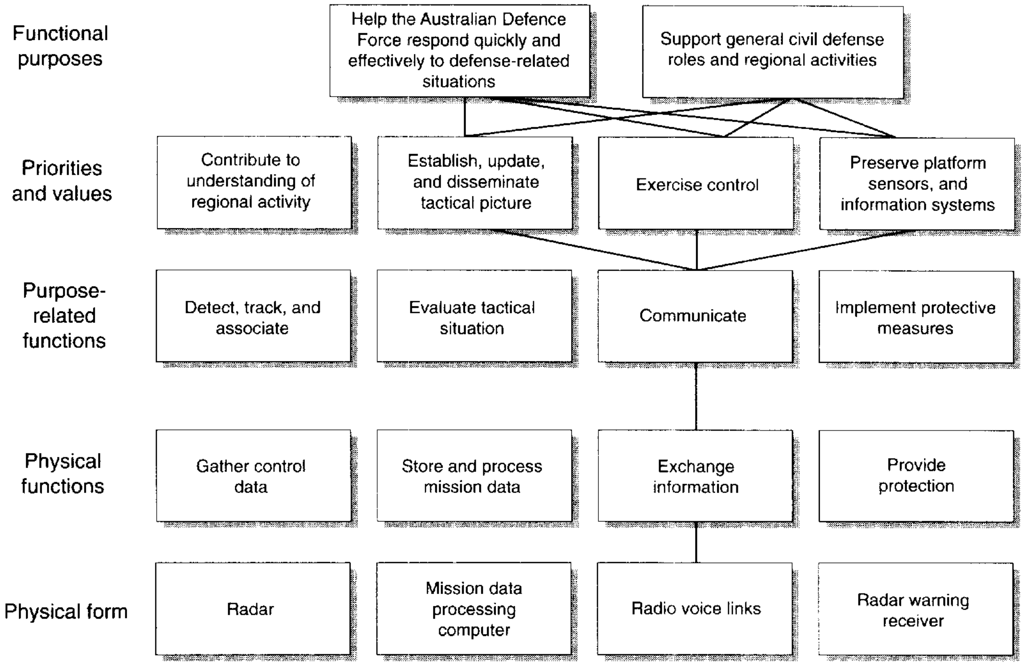

Figure 2. Sample of functions and means-ends relations from the AEW&C abstraction hierarchy.

disseminate the tactical picture and to exercise control over friendly assets is also compromised, which propagates through to all system goals. However, if the deficiency in equipment functioning is such that electronic and radio emissions are reduced, the presence of the platform will be communicated less broadly, which helps to protect the platform, sensors, and information systems from attack.

In a separate internal document, we developed detailed explanations for each of the functions and means-ends relations in the AEW&C abstraction hierarchy. We also decomposed the functions at each layer of the abstraction hierarchy into their constituent parts. For example, the function *evaluate tactical situation* was decomposed into types of tactical information, including behavior of tracks, intelligence, weather, and terrain.

Using Work Domain Analysis to Evaluate AEW&C Designs

The process for using the AEW&C work domain analysis to evaluate designs took advantage of the structure of the evaluation team that had been set up for the technical evaluation. This team was divided into subgroups (e.g., radar subgroup, communications subgroup) that were responsible for evaluating the designs of particular physical devices of the AEW&C aircraft. Each subgroup consisted of military operators and technical specialists, and each subgroup had a leader who was responsible to the head of the entire evaluation team. For the technical evaluation, each subgroup rated whether the physical devices for which they were responsible exceeded, complied with, or were deficient relative to prespecified technical performance requirements.

Following this, each subgroup evaluated the results of the technical evaluation against the purpose-related functions of AEW&C. Table 1 presents an evaluation of a *single* design (Design A); this is a hypothetical example, as information about the actual designs could not be reported here. The table lists some of the AEW&C purpose-related functions in the columns, and the reports of the radar, electronic warfare, and mission system subgroups are shown in the rows. The reports described the impact of technical enhancements or deficiencies on the purpose-related functions of AEW&C.

Where applicable, the reports described both the human and machine performance implications of the design. The evaluation groups used the explanations and decompositions of functions, which we had provided in separate internal documents, as a reference during this process.

After the subgroups had completed their reports, the head of the evaluation team, assisted by the leaders of the subgroups, summarized the overall impact (across physical devices or subgroups) on the purpose-related functions of AEW&C. Examples of such summaries are shown in the last row of Table 1. Following this step, the head of the evaluation team and his assistants (all evaluation team heads were men) evaluated the impact of the summaries at the purpose-related functions layer on the priorities and values of AEW&C. This requires a table, similar to Table 1, in which the priorities and values of AEW&C are placed in the columns and the rows describe the impact that the summaries at the purpose-related functions layer (from the last row of Table 1) have on the priorities and values of AEW&C. Finally, the summaries for each priority and value were evaluated against the functional purposes of AEW&C.

The next step was to compare the three AEW&C designs in terms of how well they supported the purpose-related functions, priorities and values, and functional purposes of AEW&C. A hypothetical comparison of three designs for some of the purpose-related functions of AEW&C is shown in Table 2. The designs were ranked in terms of how well they supported each of the functions in the AEW&C abstraction hierarchy. The overall ranking, across all functions in the abstraction hierarchy, was determined by committee. These rankings were then justified to a board of senior defense personnel.

The committee's recommendations to the board may have been contingent on factors not embedded within the work domain analysis. For example, if the committee were faced with the hypothetical situation in Table 2, they may have ranked Design A last because it breaches critical security requirements. However, they may have recommended that if the issues surrounding data linking with friendly assets could be resolved, for example, by enhancing the security of the data links while maintaining interoperability requirements, Design A should be ranked first because of the significant benefits of a radar with a long detection range. Finally, we note that the selection of the winning design was also influenced by the results of the technical and operational evaluation techniques.

Benefits and Challenges of Using Work Domain Analysis to Evaluate AEW&C Designs

When the AEW&C Project Office staff briefed the deputy secretary of the Department of Defence on the evaluation process, they singled out work domain analysis for mention because of its usefulness. Through discussion with members of the evaluation team, including those from the AEW&C Project Office, we believe there are several reasons work domain analysis was considered to be a useful approach. First, the AEW&C work domain analysis provided a set of functional criteria for integrating the results of the technical evaluation, including both human and machine performance outcomes, across all of the physical devices of AEW&C. Therefore, whereas the technical evaluation concentrated mainly on individual physical devices, work domain analysis promoted an understanding of how well an interdependent collection of human and machine components would function and interact to support AEW&C objectives. In addition, work domain analysis made it easier to select the best overall design because the three AEW&C designs could be compared systematically on a common set of criteria.

Second, the AEW&C work domain analysis shifted the focus of evaluation from technical properties (technical evaluation) to the purpose-related functions, priorities and values, and functional purposes of AEW&C. Work domain analysis was ideal for this purpose because the multiple levels of abstraction allowed evaluators to gradually shift their attention from low-level technical characteristics to high-level functions. Thus, whereas the technical evaluation led to a comprehensive understanding of the technical competence of proposed designs, work domain analysis allowed the Australian Defence Force to judge whether the technical solutions would fulfill the work requirements of AEW&C. In addition, the AEW&C Project Office found it useful that through work domain analysis, they

TABLE 1: Hypothetical Assessment of a Single Design, Illustrating How Subgroups Evaluated the Impact of Physical-Device Solutions on the Purpose-Related Functions of AEW&C

	Detect, Track, and Associate	Evaluate Tactical Situation
Radar report	Radar detection range (600 nautical miles) will enable earlier detection, tracking, and association of contacts than will original requirement.	Radar detection (600 nautical miles) will allow earlier recognition of patterns of emerging activity than will original requirement.
Electronic warfare report	The electronic support system detects a smaller number of emitters than does original requirement. This will reduce AEW&C's capability for identifying unknown entities in the environment.	The electronic support system detects a smaller number of emitters than does original requirement. This may result in an incomplete tactical picture and an inadequate understanding of the tactical situation.
Mission system report		Altitude of tracks is displayed adjacent to each track using height bars; thus altitude information will be more readily accessible in a visuospatial format, which should help operators to develop situation awareness. Original requirement was for altitude information to be displayed numerically.
Summary by head of evaluation team	Reduced coverage of electronic system will compromise identification of unknown entities. However, the enhanced radar range offers a significant advantage in detecting the existence of incoming tracks earlier. Location and activity information provided by radar is judged to be more valuable than the ability of the electronic system to identify a large number of emitters because it is a greater advantage to know the existence of a potential threat earlier than to know the specific identity of a threat. Hence the proposal exceeds the requirement for this function.	The long radar range allows track behavior to be monitored for longer and increases the likelihood of inferring the intent of a track. This will compensate for the deficiencies of the electronic support system. In addition, the visuospatial depiction of altitude may be helpful in developing and maintaining situation awareness. Thus, overall, the proposal exceeds the requirements for this function.

could express the results of the evaluation in terms of military utility to senior decision makers, who did not have the technical expertise of those on the evaluation team.

Third, whereas the operational evaluation was restricted to six mission scenarios, the AEW&C work domain analysis focused evaluation on a set of functional properties that were independent of particular events. Thus the AEW&C work domain analysis promoted a general understanding of how AEW&C designs would perform in a broad range of situations, including unanticipated events. This approach complemented the operational evaluation, which provided a detailed understanding of how the proposed designs would perform in a small range of probable AEW&C scenarios.

One of the challenges we faced in using work

TABLE 1 (continued)

Communicate	Implement Protective Measures
Communications to friendly assets will include information on tracks 600 nautical miles from AEW&C. Interception of these data communications by adversaries would reveal AEW&C radar range, breaching security requirements.	Radar detection range (600 nautical miles) will allow threats to be detected sooner and while they are farther away from AEW&C, giving AEW&C more time to respond to threats.
	The electronic support system detects a smaller number of emitters than the original requirement, but as it can detect emitters from all of the most likely threats to AEW&C, the impact on this function is judged not to be significant. The proposal does not meet the requirement for flares to be fitted to the aircraft. When at altitude, the aircraft can be protected by positioning it outside the range of infrared missiles. However, during takeoff and landing AEW&C would be vulnerable to ground-based infrared missiles. The proposal provides signature suppression significantly in excess of the original requirement, thereby greatly reducing the effective range of an adversary's infrared missiles.
Spatial audio is being offered, which will assist operators in distinguishing messages from multiple channels, thereby improving comprehension and reducing the chance of important communications being missed.	
Protecting knowledge of our radar's range is a security imperative. Therefore AEW&C must choose not to data link with friendly assets, which significantly reduces the capability of AEW&C, or the security of data links must be enhanced, which introduces difficult and expensive interoperability challenges. Thus, although spatial audio has been shown to improve people's comprehension of voice communications, the proposal does not meet the requirements for this function.	Earlier detection of threats allows timely evasive action and enhances AEW&C's ability to remain outside the range of infrared missiles at altitude. However, the platform is still vulnerable to shoulder-launched infrared weapons during takeoff and landing. Although infrared signature suppression reduces the zone of vulnerability to some extent, flares would be of greater protective benefit. Thus the proposal does not meet the requirement for this function.

domain analysis was conveying to the evaluation team that the AEW&C abstraction hierarchy represented the functional properties of the AEW&C work domain rather than the activity that occurs in the work domain. Because AEW&C is partly a physical and partly an intentional domain, this was at times difficult to distinguish as clearly as for purely physical domains, such as pasteurization plants and thermal-hydraulic process plants (e.g., Bisantz & Vicente, 1994; Reising & Sanderson, 1996). Vicente (1999) has suggested using nouns, rather than verbs, to emphasize the functional structure of a work domain. Because we intend the AEW&C work domain analysis to be a useful product throughout the life of the AEW&C system, we are currently tightening our analysis before using it further.

Another challenge in developing work domain

TABLE 2: Hypothetical Comparison of Three Designs in Terms of How Well They Support the Purpose-Related Functions of AEW&C

	Detect, Track, and Associate	Evaluate Tactical Situation
Design A	Reduced coverage of the electronic system will compromise the identification of unknown entities. However, the enhanced radar range offers a significant advantage in detecting the existence of incoming tracks earlier. The location and activity information provided by the radar is judged to be more valuable than the ability of the electronic system to identify a large number of emitters because it is a greater advantage to know the existence of a potential threat earlier than to know the specific identity of a threat. Hence the proposal exceeds the requirement for this function.	Long radar range allows track behavior to be monitored longer and increases likelihood of inferring the intent of a track. This will compensate for the deficiencies of the electronic support system. In addition, the visuospatial depiction of altitude may be helpful in developing and maintaining situation awareness. Thus, overall, the proposal exceeds the requirements for this function.
Design B	The mission computer has a maximum storage limit of 200 tracks, which will result in a large number of entities in the environment remaining untracked. Moreover, the radar has a slow update rate (10 s for scan only, 15 s with tracking), which is likely to provide inaccurate position information for tracks. Hence the proposal does not meet the requirements for this function.	The greater display size will allow operators to have more information on the screen simultaneously, but entities of interest may not be tracked because the mission computer stores a maximum of 200 tracks, thereby compromising operators' evaluation of the tactical situation. Also, the slow radar update rate will decrease operators' ability to anticipate track maneuvers. Hence the proposal does not meet the requirements for this function.
Design C	The mission system has advanced algorithms for associating tracks, which offers the potential for a greater number of track associations. Thus the proposal exceeds the requirements for this function.	Information about the height of tracks can be accessed only via a 3rd level of menu. Also, the system does not have the capability to display track history. Both these features will have a negative effect on operators' evaluation of the tactical situation. Thus the proposal does not meet the requirement for this function.
Comparison of designs	The ranking of proposals for this function is A, C, B. Design A provides a significant tactical advantage by allowing earlier detection of incoming tracks. Design C associates pairs of tracks to which operators haven't attended. However, such tracks are likely to be outside the area of significance and of limited tactical interest. Design B is significantly disadvantaged by its limited track storage capability and its radar's limited update rate.	The ranking of proposals for this function is A, B, C. Design A offers significant advantages in giving operators more time to monitor track behavior, and to infer the intent of tracks. Design B has the advantage of allowing operators to display more information on a screen. However, this advantage is outweighed by its limited track capacity and its slow radar update rate. Design C is significantly disadvantaged because operators will have no information about the history of tracks, and height information is difficult to obtain.

TABLE 2 (continued)

Communicate	Implement Protective Measures
Protecting knowledge of our radar's range is a security imperative. Therefore AEW&C must choose not to data link with friendly assets, which significantly reduces the capability of AEW&C, or the security of data links must be enhanced, which introduces difficult and expensive interoperability challenges. Thus, although spatial audio has been shown to improve people's comprehension of voice communications, the proposal does not meet the requirements for this function.	Earlier detection of threats allows timely evasive action and enhances AEW&C's ability to remain outside the range of infrared missiles at altitude. However, the platform is still vulnerable to shoulder-launched infrared weapons during takeoff and landing. Although infrared signature suppression reduces the zone of vulnerability to some extent, flares would be of greater protective benefit. Thus the proposal does not meet the requirement for this function.
The greater number of voice channels will reduce operators' workload in managing their voice communications. Thus the proposal exceeds the requirements for this function.	The faster speed at which the platform can travel will give the system more time to continue monitoring activity in the area of interest before it needs to take evasive action. Thus the proposal exceeds the requirement for this function.
The proposal offers special processing features to improve the clarity of voice communications. Moreover, the proposal offers enhanced transmit-and-receive features, which allow over-the-horizon communications. Thus the proposal exceeds the requirement for this function.	The slower speed of the platform impairs its ability to escape from threats, but the proposal offers over-the-horizon communications, which allows the platform to be positioned farther from the battlefield. Thus the proposal meets the requirements for this function.
The ranking of proposals for this function is C, B, A. Design C offers significant advantages as over-the-horizon communications would allow AEW&C to communicate with entities that would otherwise be out of range and to act as a relay station for friendly entities that are beyond communication range with their base. Design B offers a minor advantage in reducing the communications management workload, although workload is not expected to be excessive. Design A is severely disadvantaged by being unable to transmit on data links without breaching security requirements.	The ranking of proposals is B, C, A. Design B has a significant speed advantage, allowing the platform to remain on station longer and evade threats more successfully. Design C has the advantage of over-the-horizon communications, suggesting that the platform could be located farther from battle. However, its radar range is standard, so the platform will need to remain forward to retain radar coverage of the battle. Its slower speed also inhibits its ability to evade threats. Design A has a significant disadvantage in not having flares, which makes the platform vulnerable during takeoff and landing.

analysis as a standard framework for evaluation involves educating the defense acquisition community in this approach. To begin, this will require a commitment to work domain analysis from the Department of Defence. Current indications of support from senior defense personnel are encouraging. For example, the director general of aerospace development has commented that all acquisition projects should use work domain analysis. In addition, the deputy secretary of the Department of Defence has said that work domain analysis should be introduced into the acquisition cycle at stages much earlier than evaluation.

CONCLUSION

In this paper, we have shown that work domain analysis provides a useful and feasible approach for evaluating designs for complex systems. This framework focuses evaluation on how well the purpose-related functions, priorities and values, and functional purposes of a system are satisfied, given a particular technical solution. The interactions between all physical devices, including both human and machine performance outcomes, can be considered within this framework. Moreover, work domain analysis promotes an understanding of how designs will perform in a wide variety of situations, including unanticipated conditions. Work domain analysis therefore complements standard systems engineering approaches to evaluation in accommodating the special characteristics of complex systems (Table 3).

Work domain analysis also promotes a new role for human factors professionals in system design and development. This role involves working alongside systems engineers to define the total working concept for a new system (Table 3). This working concept will offer technical, operational, and functional perspectives into the new system. As the functional perspective defined by work domain analysis is tailored for integrating both human and machine performance characteristics, human factors advice will be more readily incorporated into design than in the past. More generally, work domain analysis creates a central role for human factors experts in system design and development. This too may encourage human factors to be taken more seriously than it has before.

We recognize that it may be difficult for human factors experts to convince entire organizations with well-established policies and practices to adopt novel techniques such as work domain analysis. Opportunities may arise within projects, however, for human factors experts to use work domain analysis to conduct a comprehensive evaluation of human engineering. Such bottom-up applications will help to demonstrate the power of work domain analysis to top-level managers and decision makers. In addition, this paper may be useful as a case study for illustrating the benefits of work domain analysis.

We also acknowledge that we have not yet proven that work domain analysis will lead to better designs for complex systems. However, it is difficult to test this empirically without requiring excessive resources. In addition, when

TABLE 3: Summary of How Work Domain Analysis and Systems Engineering Techniques Provide Complementary Perspectives for Evaluating Designs

Work Domain Analysis (Human-System Integration Approach)	Technical and Operational Evaluation (Systems Engineering Approach)
Evaluation focuses on the interactions between physical components	Evaluation focuses on individual components
Work requirements for evaluation defined by functional boundaries (functions, priorities and values, purposes)	Work requirements for evaluation defined by operational scenarios (sequences of tasks and events)
Evaluation is event independent and accommodates a wide range of events	Evaluation is event dependent and focuses on a small range of probable events
Human factors helps define system concept	Human factors supports systems engineering concept

work domain analysis is used on a project, such as AEW&C, it is difficult to isolate the contribution of this approach from other techniques. For these reasons, techniques for system design that are used in industry are rarely evaluated in a formal way (Czaja, 1997). Rather, the criteria that are typically used include the ability to influence practice and usefulness (Vicente, 1999; Whitefield et al., 1991). This paper shows that work domain analysis fulfilled these criteria in the case of AEW&C. The adoption of work domain analysis by others will provide further tests of this technique against these criteria.

Finally, although we have focused on using work domain analysis for evaluating designs, this approach is also useful much earlier in the system life cycle for defining functional requirements and specifications (Leveson, 2000; Naikar & Sanderson, 1999). Work domain analysis can also be used throughout system development – for example, for defining training needs, designing team work, and for operational test and evaluation (Naikar, Drumm, Pearce, & Sanderson, 2000; Naikar et al., in press; Naikar & Sanderson, 1999; Sanderson et al., 1999). Hence, although work domain analysis is initially resource intensive, it can be used repeatedly, in many powerful ways, throughout the life of a system.

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